About Exam 3

- When and where (same as before)
  - Monday Nov. 22\textsuperscript{nd}: 5:30-7:00 pm
  - Bascom 272: Sections 301, 302, 303, 304, 305, 311, 322, 327, 329
  - Ingraham B10: Sections 306, 307, 312, 321, 323, 324, 325, 326, 328, 330
- Format (same as before)
  - Multiple choices
  - Close book
  - One 8x11 formula sheet allowed, must be self-prepared.
  - Bring a calculator (but no computer). Only basic calculation functionality can be used.
- Special needs:
  - No early test before Monday Nov 22\textsuperscript{nd} possible.
  - One alternative session (Monday afternoon) in our lab room
  - Please email me for request/approval before next Monday!

Sources of $\mathbf{E}$ and $\mathbf{B}$ Fields

- Sources for the electric field:
  - Electric charges (Coulomb’s Law, static)
  - Change of $\mathbf{B}$ field (Faraday’s Law, varying in time)
- Sources for the magnetic field:
  - Electric current (Biot-Savart Law/Ampere’s Law, static)
  - Change of $\mathbf{E}$ field (Ampere-Maxwell Law, varying)

$\Rightarrow$ All these features are summarized in Maxwell Equations.

Maxwell Equations

\[
\oint \mathbf{E} \cdot d\mathbf{A} = \frac{q}{\varepsilon_0} \quad \Rightarrow \text{Gauss’s Law/Coulomb’s Law}
\]
\[
\oint \mathbf{B} \cdot d\mathbf{A} = 0 \quad \Rightarrow \text{Gauss’s Law of Magnetism, no magnetic charge}
\]
\[
\oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt} \quad \Rightarrow \text{Faraday’s Law}
\]
\[
\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I + \varepsilon_0\mu_0 \frac{d\Phi_E}{dt} \quad \Rightarrow \text{Ampere-Maxwell Law}
\]

Also, Lotentz force Law $\Rightarrow \mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$

These are the foundations of electromagnetism.

Physics 202, Lecture 21

Today’s Topics

- Electromagnetic Waves (EM Waves)
- Maxwell’s equation
- Speed of EM Waves
- The Hertz Experiment
- EM Wave Spectrum, Wavelength and Frequency
- Antenna
- How to make a “HDTV” Antenna?
Ampere’s Law Revisited

- A magnetic field is produced by an electric current is given by the Ampere’s Law:
  \[ \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I \]

- A changing electric field will also produce a magnetic field.

Finally:

\[ \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I + \varepsilon_0 \mu_0 \frac{d\Phi_E}{dt} \]

\( \varepsilon_0 \): permittivity of free space (a constant)
\( \mu_0 \): permeability of free space (also a constant)

“Displacement current”.

Demo: Hertz Experiment

In 1887, Heinrich Hertz first demonstrated that EM fields can transmit over space.

EM Fields in Space

- Maxwell equations when there is no charge and current:
  \[ \oint \mathbf{E} \cdot d\mathbf{A} = 0 \]
  \[ \oint \mathbf{B} \cdot d\mathbf{A} = 0 \]
  \[ \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt} \]
  \[ \oint \mathbf{B} \cdot d\mathbf{l} = \varepsilon_0 \mu_0 \frac{d\Phi_E}{dt} \]

Differential forms:

\( \frac{\partial E_y}{\partial t} = -\frac{\partial B_z}{\partial x} \)
\( \frac{\partial B_z}{\partial x} = -\mu_0 \varepsilon_0 \frac{\partial E_y}{\partial t} \)
\( \frac{\partial^2 E_y}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E_y}{\partial t^2} \)
\( \frac{\partial^2 B_z}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B_z}{\partial t^2} \)
Linear Wave Eq. and Solutions (Ch. 16)

- Wave function for a propagating wave: \( y(x,t) = f(x-\nu t) \)
- Linear Wave equation and harmonic waves

\[ \frac{\partial^2 y}{\partial x^2} = \frac{1}{\nu^2} \frac{\partial^2 y}{\partial t^2} \]

\[ y = A \sin(\frac{2\pi}{\lambda} x - 2\pi \nu t + \phi) \]

**Wave speed**
- \( \nu = \frac{\lambda f}{c} \) if \( \nu = \frac{2\pi}{\lambda} \)
- \( k = 2\pi/\lambda \)
- \( \omega = 2\pi f \)

Electromagnetic Waves

- **EM wave equations:**
  \[ \frac{\partial^2 E}{\partial x^2} = \frac{\mu_0 \varepsilon_0}{\mu_0 \varepsilon_0} \frac{\partial^2 B}{\partial t^2} \]
- **Plane wave solutions:**
  \[ E = E_{\text{max}} \cos(kx-\omega t+\phi) \]
  \[ B = B_{\text{max}} \cos(kx-\omega t+\phi) \]

Two polarizations possible (here showing one)

Electromagnetic Waves

- **In vacuum**
  \[ c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 2.9972 \times 10^8 \text{ m/s} \]
- **EM wave can transmit in vacuum**

**Wavelength and Frequency Relationship:**

\[ \lambda f = c = 3 \times 10^8 \text{ m/s} \]

**Great significance:**
1. EM waves exist in vacuum;
2. Speed of wave (light) finite;
3. Superposition: interference, diffraction;
4. Polarizations.
Spectrum of EM Waves

Wavelength and frequency relationship for EM wave
\[ \lambda f = c = 3 \cdot 10^8 \text{ m/s} \] in vacuum

Example: Determine the wavelength (in air) of an EM wave of frequency 687 MHz (HDTV channel 3, CBS = UHF ch. 50)

\[ \lambda = \frac{c}{f} = \frac{3 \cdot 10^8 \text{ m/s}}{687 \text{ MHz}} = \frac{3 \cdot 10^8 \text{ m/s}}{6.87 \cdot 10^8 \text{ s}^{-1}} = 0.44 \text{ m} \]

- VHF: \( \lambda \approx 1-10 \text{ m} \)
- UHF: \( \lambda \approx 0.1-1 \text{ m} \)
- Over-The-Air (OTA) DTV channels:
  - 90% of them in UHF band \( \Rightarrow \lambda \approx 0.4 - 0.6 \text{ m} \)

Half-Wave Antenna

Standing Wave Condition (ch. 18)

Various RF Antennas